Reliability and Radiation Hardness of Compound Semiconductors

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Abstract – **A thorough understanding of reliability and radiation hardness is required in order to use compound semiconductors in space, or in other environments involving radiation and/or extended temperature operation. This paper discusses those issues for several types of compound semiconductors that are of interest for high-performance applications.**

I. INTRODUCTION

This paper discusses reliability and radiation hardness of mainstream compound semiconductor devices. The material discussed in the paper draws on recent material in the literature as well as experience of the authors in evaluating compound semiconductor devices for space applications. Conventional concepts of reliability and radiation hardness are reviewed and compared with trends in more advanced devices.

Three basic types of compound semiconductor devices are considered in this work. The first category is that of discrete transistors, fabricated with heterostructures, primarily intended for applications in very high frequency or microwave applications. The second category is integrated and hybrid circuits, including MMIC devices. The third category is optoelectronics. We will limit the discussion to reliability and radiation effects in optical emitters – light emitting diodes and laser diodes – in this paper.

One of the key points in the paper is that reliability and radiation effects in compound semiconductors involve different effects and mechanisms compared to silicon technology semiconductors, which have been the focus of most work on these topics. Different methodologies are required to deal with compound semiconductors that may not be a straightforward extension of the knowledge base that exists for silicon technology. The main issues are dealing with emerging types of semiconductors, where there is limited experience in manufacturing and reliability; and device technologies with extremely small dimension.

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II. BACKGROUND

A. Reliability Issues

The recent growth of the compound semiconductor industry has resulted in substantial improvements in processing methods, fabrication yield, and overall quality of commercially viable compound semiconductor devices. This, coupled with large volume production and the utilization of statistical process control, has greatly reduced the infant mortality population without having to impose traditional high reliability part specifications. However, reproducibility of a product does not guarantee reliability in the intended application. For critical space applications where the success or failure of a mission hinges on the lifetime and performance of a single device; it is critical that all aspects of the reliability and the various known failure modes and mechanisms be addressed prior to the insertion of the component in the application [1].

The selection and application of microelectronic components in high reliability space systems requires knowledge of the component design, fabrication process, and applicable tests. In addition, reliability analysis and detailed knowledge of the application environment are necessary to determine the suitability of the selected component for the application. These issues are of particular importance for the application of compound semiconductor devices in high reliability systems due to the need for the utilization of large numbers of these devices at the upper limit of their performance and stress capabilities.

The user of compound semiconductor devices must gain an understanding of not only the technology performance capabilities but also of the limitations of the technology and must employ methods to utilize it in a reliable fashion. The user must also understand that many of the failure mechanisms associated with silicon devices do not apply to GaAs and other compound semiconductors, and that new device structures bring new failure mechanisms. In addition, many of the traditional assumptions for mean-time failure rate predictions do not hold for those new devices. Thus, today's high reliability user must be more aware of measurement-based predictions of long term failure rate over calculation based predictions.

This article provides a brief overview of reliability issues relating to compound semiconductor devices and some common practices for determining suitability of these devices for application in high reliability space systems.

B. Radiation Environments

Fundamental Interactions. Five types of particles are usually considered in radiation environments: gamma rays, electrons, protons, neutrons, and energetic nuclei from space or from nuclear fission.

Gamma rays and electrons are often lumped together because the primary way in which they lose energy is through ionization. Ionization produces electron-hole pairs within semiconductors and insulators. This can cause charge to be trapped at interfaces between semiconductors and insulators. Although that mechanism is extremely important for silicon devices, it is much less important for compound semiconductors because insulating materials do not exist in compound devices with the high quality and low interface state density that is present in silicon dioxide. Consequently, most compound semiconductors are relatively immune to ionization radiation damage at levels below 1 Mrad(GaAs) [2].

Protons also produce ionization, but they also interact with lattice atoms, where they can impart sufficient energy to move atoms from their normal lattice position to a resting point that can be up to 1000 angstroms away from the starting point. These displacement effects introduce a great deal of damage in the lattice. Neutrons produce similar displacement effects. Displacement damage has three important effects. Minority carrier lifetime is reduced; carrier mobility is reduced; and the effective doping level can be altered because of carrier removal. Displacement damage is generally far more important than ionization damage for compound semiconductors, and that will be the main focus of Section V.

High-energy nuclear particles also produce displacement damage and ionization. However, the most important consideration is usually single-event upset, not permanent damage effects. Single-event upset is a circuit effect that occurs because the interaction of a *single* charged particle produces a small but significant amount of charge that can be collected at sensitive circuit nodes, causing the stored information in a memory or flip-flop to be altered. Integrated circuits manufactured with compound semiconductors can be very sensitive to single-event upset effects.

Space Environments. Space environments can generally be divided into (a) permanent damage effects from high-energy electrons and protons that produce uniform damage within each individual region of a semiconductor device, and (b) highly localized ionization or displacement effects from the single interaction of a cosmic ray or trapped proton.

Radiation levels for typical spacecraft are summarized in Table 4, assuming that a 100-mil aluminum shield surrounds the electronics within the spacecraft. The shield is very important because it removes most of the low energy particles from the environment. Planetary space missions that go near Jupiter have very high radiation requirements because of intense trapped radiation belts that extend to very large distances.

Table 1
Total Dose Requirements for Representative Space Missions

Description	Orbit	Operating Time (years)	Total Dose rad(SiO_2)
Space Station	500 km 54 degree	10	5×10^3
High-inclination earth orbiter	705 km 98 degree	5	2×10^4
Geostationary	36,000 km	5	5×10^4
Mars Surface Exploration	NA	3	10^4
Mission near Jupiter	NA	9	$1.5 \times 10^5 - 2 \times 10^6$

Requirements for single-event effects are much more difficult to define because there is a distribution of ion types and energies in space, as well as solar activity. Proton single-event upset is also influenced by the South Atlantic anomaly in the earth's trapped radiation belts. See References 3 and 4 for more details. The error rate for memory cells or registers is usually used as a benchmark for single-event upset. Commercial silicon-based devices have error rates on the order of 10^{-6} to 10^{-8} errors per bit day in a deep space or geostationary environment. It is often possible to use error-detection-and-correction or other system level approaches to deal with these types of upset effects. The alternative is to use special hardened circuits. As discussed in Section V, logic circuits that use compound semiconductors are somewhat more sensitive to single-event upset than comparable silicon technologies. However, compound semiconductor structures do not exhibit latchup or other catastrophic failure effects, which is an advantage in space applications.

Nuclear Reactor Environments. For nuclear reactors, the primary concern is displacement damage from neutrons and decay products from activated material, and ionization damage. Very high radiation levels – in the multi-Megarad region - are often required, particular for worst-case operational scenarios. Many compound semiconductor devices are highly resistant to ionization and displacement damage, making them good candidates for use at nuclear reactor facilities.

III. COMPOUND SEMICONDUCTOR CONSTRUCTION AND PHYSICS

A. Typical Materials

Initial work was done by extending the principles of silicon technology, adding dopants to GaAs to produce p-n junctions with a single semiconductor type (homogeneous semiconductor junctions). The much higher electron mobility of GaAs provides a significant advantage in high-frequency devices. Earlier work concentrated on MESFET structures. In 1978 heterostructures were developed that allowed new material combinations to be developed [5], although the concept of heterostructures was first proposed by William Shockley. The initial material combination was AlGaAs on GaAs substrates. This work was extended to other material types, using advanced processing techniques such as liquid-phase growth and molecular beam epitaxy to form precisely controlled layers of different material types and dopants. These processes allow very thin layers to be formed, providing the ability to form extremely thin regions of different semiconductor materials. Quantum-well structures can be deliberately fabricated with these techniques. One of the key properties of heterojunctions is that the barrier between the materials is mainly determined by bandgap difference, not by bias conditions. This allows junctions to be formed in extremely narrow regions.

Several different material combinations can be used for compound semiconductor junctions. The key properties are the bandgap, which can be tailored by varying the material composition; and lattice mismatch, which generally must be below 0.2% in order to minimize defects that reduce mobility. The table below shows a AlGaAs alloy and InGaAs alloy that are lattice-matched to GaAs, as well as an InGaAs alloy that is lattice-matched to InP. Many other material combinations have been developed.

Table 2
Properties of Some Compound Semiconductor Alloys

Material	Electron Mobility (cm^2-s/V)	Lattice Constant	Eg (eV)
GaAs	8500	5.65	1.42
$Al_{0.3}Ga_{0.7}As$	2300	5.66	1.65
$In_{0.15}Ga_{0.85}As$	5800	5.71	1.05
InP	4600	5.87	1.35
$In_{0.53}Ga_{0.47}As$	13,000	5.87	0.78

Other factors that are important for compound semiconductors are materials and growth methods for contacts. Thermal conductivity is another key property. Note for example that the thermal conductivity of GaAs is only about 1/3 that of silicon. The thermal conductivity of SiGe is also much lower than for silicon. These are key parameters in the design of devices that operate at high power densities, such as RF amplifiers, but are less important for high-speed logic circuits.

B. Strained Lattices

Earlier material development for heterojunctions assumed that a close lattice match was required in order to keep the defect density at acceptable levels. However, it is possible to accommodate strain within the lattice if the lattice dimensions are kept below a critical thickness, usually < 100 Å. Lattice mismatch up to 1.5% can be used in strained lattices.

Strained materials not only allow a wider range of options for "bandgap engineering" but can also modify material properties. By introducing selected amounts of strain, it is possible to increase both electron and hole mobility. This can improve the performance of heterojunction bipolar structures [6]. Strained layers are frequently used in silicon-germanium HBTs, as well as in laser diodes (see the discussion in III-C, below). Although it would appear that strained layer devices would be less reliable than conventional semiconductors, extensive work has been done that demonstrates comparable reliability between strained and unstrained materials in a given technology as long as the misfit between the different materials is not too large [7].

C. Transistor Technologies

MESFETs and HFETs. GaAs MESFETs were the first compound semiconductor device to be widely used, particularly for microwave applications. The

basic principles are similar to those of silicon MESFETs, with smaller dimensions in order to optimize high-frequency performance. Most GaAs MESFETs are fabricated on semi-insulating substrates, which affects their radiation performance (see Section V).

Heterostructure field-effect transistors (HFETs) use thin layers of different materials to allow quantum-mechanical confinement of carriers within the active region. The earliest HFETs used Schottky gates, but it is also possible to fabricate HFETs with insulating gate structures. Many different material systems can be used, including strained layers. It is possible to produce complementary transistors with HFET technology, providing a major advantage over MESFETs for high-performance logic. The main applications of HFETs are in very high-speed and low-noise applications. Cost and yield prevent direct competition with large-scale silicon devices, but HFETs are selectively used in many applications that require high speed, including fiber optic data busses and RF communication systems.

Heterojunction Bipolar Transistors. Heterojunction bipolar transistors have been developed using the bandgap discontinuity between the emitter and base materials for carrier injection. This allows the base width to be reduced to about 0.1 µm. It also allows transistors to be fabricated with heavily doped base regions [8]. The net effect is a very compact transistor with high gain and very high gain bandwidth product.

Modern HBTs can achieve gain-bandwidth products of 100 GHz or more [9]. SiGe, InP and InGaAs heterostructures have been used in advanced heterojunction bipolar devices. HBTs have many commercial applications, and further development of these technologies is an area of active research.

D. Optical Devices

Additional material properties are important for optical devices. For LEDs and laser diodes, photon containment requires that the index of refraction in the confined (active optical) layer is less than the index of refraction of surrounding layers. Another key property is the band structure. Efficient optical transitions are only possible for materials with direct bandgap. Figure 1 shows how bandgap and wavelength can be tailored for AlGaAs/GaAs heterostructures. When the mole fraction of aluminum exceeds 0.45, the bandgap becomes indirect. Thus, that limits the shortest wavelength to about 630 nm for that material system. However, by

varying the composition it is possible to use AlGaAs alloys for optical devices with wavelengths between 630 and 950 nm.
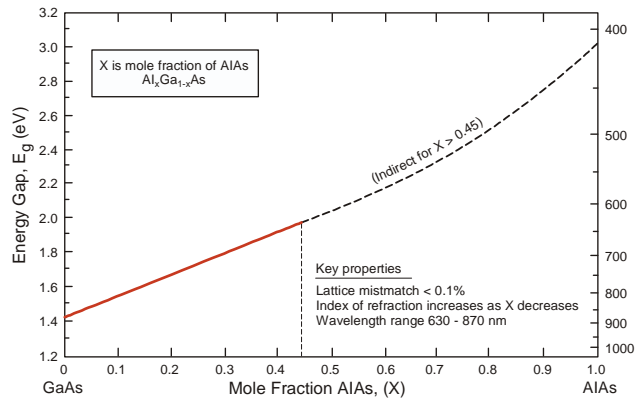

Figure 1. Effect of material composition on wavelength for AlGaAs/GaAs

Other material combinations can also be used, such as the three material systems shown in Table 3. InGaAsP/InP is usually used in strained layer lasers, where the presence of strain increases hole mobility, decreasing the threshold current of the laser by as much as a factor of two [10,11].

Table 3

Material Combinations Used for Optical Emitters in the Visible and Near Infrared Regions of the Spectrum

Material Combination	Wavelength Range (µm)
AlGaAs/GaAs	650 - 850
InGaAsP/InP	1100 - 1600
InGaAs/GaAs	900 - 1100

IV. RELIABILITY

A. Conventional Reliability Concepts

Device reliability involves probability statistics, time, and a definition of failure. Given a failure criterion, the most direct way to determine reliability is to submit a large number of samples to actual use conditions and monitor their performance against the failure criteria over time. Since most applications require device lifetimes of many years, this approach is not practical. To acquire device reliability data in a reasonable amount of time, an accelerated life test at high temperatures is used. This type of accelerated test is based on the observation that most failure mechanisms are thermally activated. By exposing the

devices to elevated temperatures, it is possible to reduce the time to failure of a component, thereby enabling data to be obtained in a shorter time than would otherwise be required. Such a technique is known as "accelerated testing" and is widely used throughout the semiconductor industry. The rate at which many chemical processes take place is governed by the Arrhenius equation:

$$R = A \exp(-E_a/kT) \qquad (1)$$

where

R = rate of the process
A = a proportional multiplier
E_a = activation energy, a constant
k = Boltzmann's constant, 8.6×10^{-5} (eV/K)
T = Absolute temperature in Kelvin

This equation has been adopted by the semiconductor industry as a guideline by which the operation of devices under varying temperature conditions can be monitored. Experimental data obtained from life tests at elevated temperatures are processed via the Arrhenius equation to obtain a model of device behavior at normal operating temperatures. Rearranging the Arrhenius equation allows the temperature dependence of component failure to be modeled as follows:

$$\ln t_2/t_1 = E_a/k \, (1/T_2 - 1/T_1) \qquad (2)$$

where

$t_{1,2}$ = time to failure
E_a = activation energy in electron volts
T = absolute temperature in Kelvin

B. Common Failure Mechanisms

Several failure mechanisms are important for compound semiconductors that either have no counterpart in silicon technology, or are not significant issues.

Failures in electronic devices can be classified as either catastrophic failures or degradation failures. The exact mechanism that causes failure is normally dependent on the material structure, processing methods, application, and stress conditions. Device bias, resultant channel temperature, passivation, and material interactions may all cause or contribute to different failure mechanisms. Furthermore, device

handling, choice of materials for packaging and the application environment may also cause failures. Some common failure mechanisms affecting the device at die level are discussed below:

Gate-Metal Sinking: The performance of GaAs-based devices relies heavily on the quality of the active channel area of the device. The Schottky gate metal-to-semiconductor interface directly influences the device electrical parameters, such as the drain saturation current and reverse breakdown. The gate structures are based on the industry standard multi-layer Au/Pt/Ti or Au/Pd/Ti on GaAs. Inter-diffusion of gate metal with GaAs results in a reduction of the active channel depth and a change in the effective channel doping. This effect is termed "gate sinking." This process is affected by the surface conditions of the GaAs material at the time of deposition, the deposition parameters, and the choice of deposited materials [12,13].

Ohmic Contact Degradation: The most common system for ohmic contacts is AuGe/Ni, which is alloyed into the GaAs at temperatures in excess of 400°C to provide the necessary low contact resistance (0.1 to 0.5 Ω/mm). A thick Au layer is then deposited on top of the alloyed contacts to provide conduction. This structure, employed at the drain and source contacts, has been shown to degrade at elevated temperatures (>150 °C). The degradation is the result of Ga out-diffusion into the top Au layer and the diffusion of Au into the GaAs causing an increase in the contact resistance. The Ni layer used in the ohmic contact is intended as a Au- and Ga-diffusion barrier. Some other materials such as Cr, Ag, Pt, Ta, and Ti have been used as barrier materials with varying degrees of success [14]. The activation energy associated with ohmic contact degradation varies between 0.5 eV and 1.8 eV. This activation energy may provide reasonable contact life at low operating temperatures (<100 °C) but it also indicates rapid deterioration at elevated temperatures [15].

Channel Degradation: Degradation observed in device parameters can sometimes be attributed to changes in the quality and purity of the active channel area and a reduction in the carrier concentration beneath the gate Schottky contact area. These changes have been postulated to be a result of diffusion of dopants out of the channel or diffusion of impurities or defects from the substrate to the channel. Deep level

traps have also been postulated to cause similar degradation in MESFETs [16].

HEMT devices, being strongly dependent on the properties of the interface of the AlGaAs/GaAs heterostructure, can suffer a related failure mechanism. A decrease in electron concentration in the channel, caused by a de-confinement of the 2-Dimensional Electron Gas (2DEG), was postulated to be the cause of the observed failure mechanism.

HEMT devices can also suffer from metal-diffusion-related mechanisms, which are manifested as channel-related degradation. Lateral diffusion of Al into the gate recess region changes the conduction band discontinuity and consequently the confinement of the channel electrons. Gold diffusion from the ohmic contact into the active channel region under the gate can also cause similar degradation. Lastly, vertical diffusion of Al from the AlGaAs donor layer and Si from the n^+ AlGaAs layer into the channel layer causes an increase in the impurity scattering in the undoped GaAs, thus deteriorating the high electron mobility of the 2DEG [17].

Surface State Effects: The performance of GaAs-based devices depends highly on the quality of the interface between metal and GaAs or the passivation layer (Si_3N_4 or SiO_2) and GaAs. The quality of the interface can depend on the surface cleaning materials and procedures, the deposition method and conditions, and the composition of the passivation layer. As shown in Fig. 2, the main effect of an increase in surface state density is the lowering of the effective electric field at the drain/gate region, which results in an increase in the depletion region and a change in the breakdown voltage.
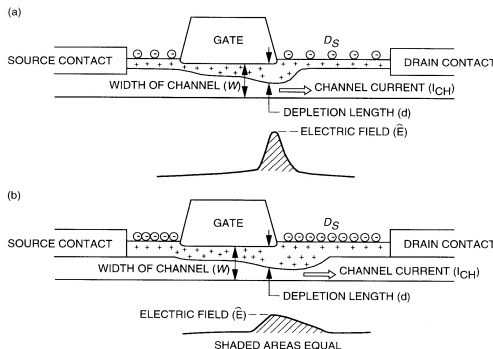
Figure 2. Schematic cross section of a MESFET with different surface charges. (a) with low density of surface states, and (b) with high density of surface states[18].

Unpassivated devices can be susceptible to surface oxidation and loss of arsenic, which may result in an increase in gate leakage current and a reduction of the breakdown voltage. Devices passivated using SiO_2 may experience surface erosion due to the interaction of SiO_2 with GaAs [19].

Electromigration: The movement of metal atoms along a metallic strip due to momentum exchange with electrons is termed electromigration. Since the mechanism is dependent on momentum transfer from electrons, electromigration is dependent on the temperature and number of electrons. Therefore, this failure mechanism is generally seen in narrow gates and in power devices where the current density is greater than $2x10^5$ A/cm^2, which is normally used as a threshold current density for electromigration to occur. As shown in Fig. 3, this effect is observed both perpendicular and along the source and drain contact edges and also at the interconnect of multilevel metallizations.
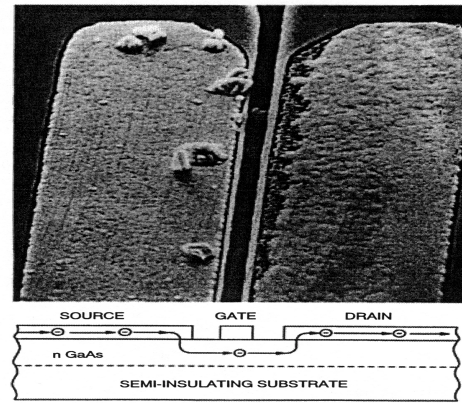
Figure 3. Depletion and accumulation of material in AuGeIn source and drain ohmic contacts induced by electromigration.

The metal atoms that migrate along the line tend to accumulate at the grain boundaries. The accumulation of metal at the end of the gate or drain contact can create fingers of metal that can short the device. Material accumulation and void formation perpendicular to the source and drain contacts can cause hillock formation over the gate structure. This may result in shorting the gate to the source or drain that may result in catastrophic failure.

Hot Electron Trapping: Under RF drive, hot electrons are generated near the drain end of the channel where the electrical field is the highest. A few electrons can accumulate sufficient energy to tunnel into the Si_3N_4 passivation to form permanently charged traps. As shown in Fig. 4, these traps can

result in lower open-channel drain current, transconductance, higher knee voltage, increased leakage current, and decreased breakdown voltage. Since the traps are located above the channel, there is usually little change in the dc or small signal parameters near the quiescent point. Further, since the traps are located beside the channel, Schottky-barrier height and the ideality factor often remain constant. This selective change in device characteristics helps distinguish hot-electron effects from thermal or environmental effects [20].
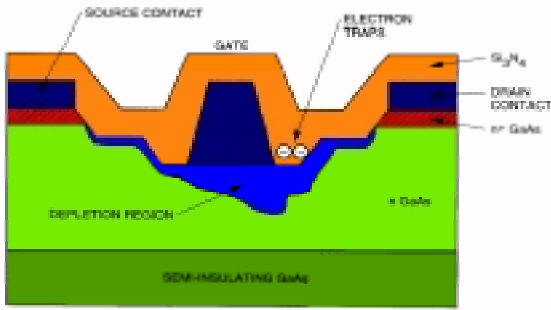

Figure 4. Location of electron traps after tunneling into passivation regions.

Hydrogen Effects: Degradation in I_{DSS}, V_p, g_m, and output power was observed on GaAs and InP devices tested in hermetically sealed packages or under hydrogen atmosphere. The source of the degradation has been attributed to hydrogen gas desorbed from the package metals (Kovar, plating, etc.). The exact mechanism by which hydrogen degrades the device performance and the path by which hydrogen reaches the active area of a device are not known and have been under investigation [21].

Earlier research, [22], on GaAs transistors identified the diffusion of atomic hydrogen directly into the channel area of the device where it neutralizes the silicon donors as the possible mechanism. It is believed that atomic hydrogen diffuses into the GaAs channel and forms Si-H, thereby neutralizing the donors. Experiments have shown that exposure of Si-doped GaAs to RF hydrogen plasma results in neutralization of the Si donors. Infrared spectroscopy data have also given evidence of $(SiAs_3)As$-H complexes[23].

The neutralization of donors can decrease the carrier concentration in the channel, which, in turn, can decrease the drain current, transconductance, and gain of the device. Hydrogen effects in FETs with either Pt or Pd gate metals have been observed. Recent research has concluded that the diffusion of hydrogen may occur at the Pt side-walls and not at the Au surface of the Au/Pt/Ti gate metal [24].

Other research, an example of which is shown in Fig. 5, on GaAs PHEMT and InP HEMT in a hydrogen atmosphere has shown that the drain current may increase in some cases. This observation has led to the conclusion that the hydrogen diffuses into the semiconductor surface where it is thought to change the metal-semiconductor built-in potential.
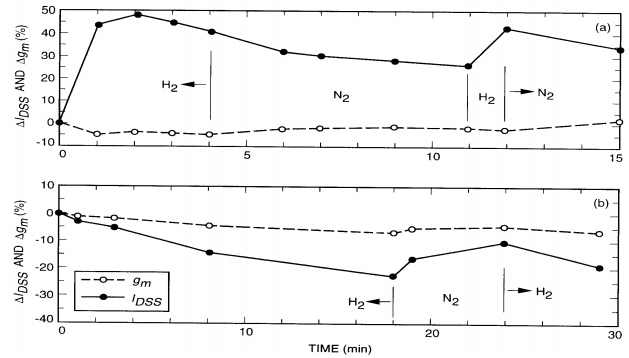

Figure 5. Changes in peak transconductance,g_m, and drain current at zero bias, I_{dss}, of (a) InP HEMT and (b) GaAs PHEMT under nitrogen and 4% hydrogen treatment at 270°C[18].

Manufacturers and users of GaAs devices used in hermetically sealed packages are currently pursuing an acceptable solution to this problem. Some of the possible solutions include thermal treatment of the packaging materials to reduce the amount of desorbed hydrogen after the seal, the use of hydrogen getter materials in hermetically sealed packages, and the use of barrier materials that do not contain the Pt/Ti or Pd/Ti structure. These solutions have limitations and possible instability problems that must be fully understood prior to implementation in high reliability systems.

Packaging Effects: The package serves to integrate all the components required for a system application in a manner that minimizes size, cost, mass and complexity. In doing so, the package must provide for mechanical support, protection from the environment, a stable thermal dissipation path, and electrical connection to other system components. For compound semiconductors, the package must satisfy all these characteristics and allow for reliable device performance over a wide range of conditions.

Understanding the packaging effects on the reliability of compound semiconductors is essential to

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attaining a reliable space system. In most applications, packaging of compound semiconductor devices is similar to that developed for silicon based technologies. However, the choice of packaging materials plays more of a critical role due to differences in the coefficient of thermal expansion. In addition, compound semiconductors are more fragile and may exhibit mechanical stresses causing device degradation and failure.

The stability and reliability of the die attach is largely determined by the ability of the structure to withstand the thermo-mechanical stress created by the difference in the Coefficient of Thermal Expansion (CTE) between the die and the packaging material. These stresses are concentrated at the interface between the die and the die-attach material and the interface between the die-attach material and the package [25]. The Coffin-Manson relation relates the number of thermal cycles a die attachment can withstand before failure:

$$Nf \propto \gamma^m \{2*t/L*\Delta CTE*\Delta T\} \qquad (3)$$

where

γ = shear strain for failure

m = constant dependent on the material

L = diagonal length of the die

t = die-attach material thickness

The number of thermal cycles before failure can be significantly reduced by the presence of voids in the die attach material, since voids cause areas of concentrated localized stress which can lead to premature die delamination. In addition, voids cause localized heating which in turn causes an increase in the thermal resistance of the die attach material leading to device degradation and possible catastrophic failure.

Infrared imaging techniques can provide for a qualitative and sometimes a quantitative measure of the adequacy of the thermal path and a visual representation and mapping of possible void locations. Figure 6 shows a comparison of an optical and an Infrared image of the same die.
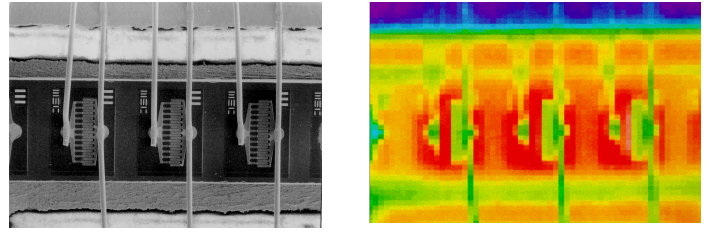

Figure 6. Optical(left) and IR image (Right) of the same die. The IR image shows thermal gradient and location of hot spots and possible void locations.

Light-Emitting and Laser Diodes. Power output from optical emitters can change during operation. The high internal optical power density in those devices causes different wearout mechanisms to occur compared to conventional electronic components. In some cases the degradation is gradual, while in others sudden, catastrophic damage occurs. Facet damage in laser diodes is an example of catastrophic damage [26]. It is caused by localized heating, due to very high localized optical power levels. It is a more severe problem for AlGaAs than for other laser materials. Another degradation mechanism is associated with internal crystal dislocation defects, which grow during operation (referred to as dark-line defects, or DLDs) [27]. DLDs can produce abrupt changes in the threshold characteristics of laser diodes over operating times of several hundred hours or longer, or may develop more gradually over extended time periods. A third mechanism is attributed to gradual increase of point defects, increasing non-radiative recombination losses. That mechanism can occur for both laser diodes and LEDs, with a typical activation energy of 0.5 eV.

Although earlier laser diode technologies had very limited operating life, improvements in laser diode technology have decreased the internal power densities by many orders of magnitude, increasing reliability to the point where operation over periods of 10,000 hours or more can be achieved [28]. The reliability of strained-layer lasers has comparable reliability [29]. Note, however that achieving high operating lifetime requires derating below the maximum operating power levels.

LEDs operate at lower power densities than laser diodes, but they also degrade during operation. Non-radiative defects gradually increase with time, changing the slope of the I-V characteristics as well as decreasing light output. The rate of the increase depends on operating conditions and temperature, and varies for different samples. In some cases LEDs undergo rapid initial decrease in light output, followed by a plateau region. The initial rapid decrease is due

to dark-line defects, which cannot be described by the Arrhenius model. The gradual degradation region does follow the Arrhenius relationship, with an activation energy of about 0.6 eV [30].

Although a great deal of information is available about LED reliability in conventional environments, one of the key issues for space applications is whether wearout effects can be considered separately from the degradation that occurs from space radiation. Wearout data for light-emitting diodes is shown in Figure 7. Three different LEDs were subjected to an extended test, using the maximum recommended operating current. The devices were operated with a heat sink to keep the case temperature at 25 ºC. Note the gradual deterioration in output power. Radiation tests on aged samples showed that aging and radiation damage could be considered separately, with no synergistic effects even though both environmental stress conditions decrease power output and increase the forward voltage required at a given light output [31]. However, it should be noted that much less degradation occurs when the LEDs are operated at low power compared to the maximum rated value. For example, tests of a different sample of the devices in Figure 7 at 50 mA instead of 100 mA decreased the degradation by about a factor of five at the longest operating times.
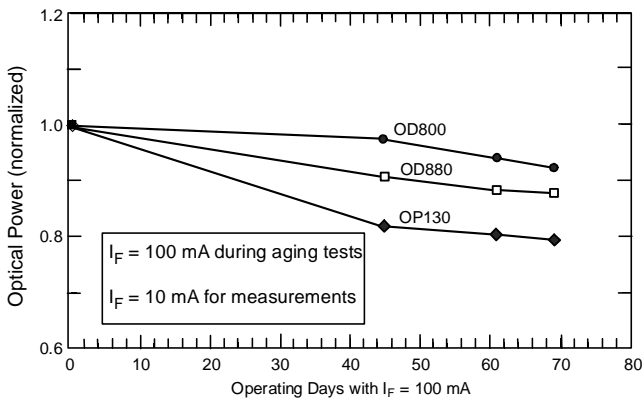

Figure 7. Degradation of light-emitting diodes with operating time. The devices were kept at room temperature during the aging tests.

V. RADIATION HARDNESS

A. Ionizing Radiation Damage

Although ionizing radiation is often one of the dominant radiation problems for devices made with silicon technology, ionization is usually of secondary importance for compound semiconductors. The basic reason is that it is not possible to make extremely high-quality insulators (such as SiO_2) in compound semiconductor systems.

Figure 8 shows how electron damage affects InP/InGaAs heterojunction bipolar transistors [32]. Very little damage occurs until the total dose is above 50 Mrad, even at low current densities. For comparison, silicon transistors can exhibit large decreases in gain at total dose levels between 10 and 50 krad(SiO_2). Although not all compound semiconductors are as robust as the InP device in Figure 8, they generally show little degradation until radiation levels above 10 Mrad(GaAs).

Older work on MMIC devices has shown similar radiation hardness for 30 GHz microwave integrated circuits that used GaAs MESFETs [33]. Changes in power gain first started to occur at 10 Mrad(GaAs), and the devices were useable to levels of about 50 Mrad(GaAs). Thus, both bipolar and MESFET structures are only affected by ionizing radiation after exposure to very high radiation levels.
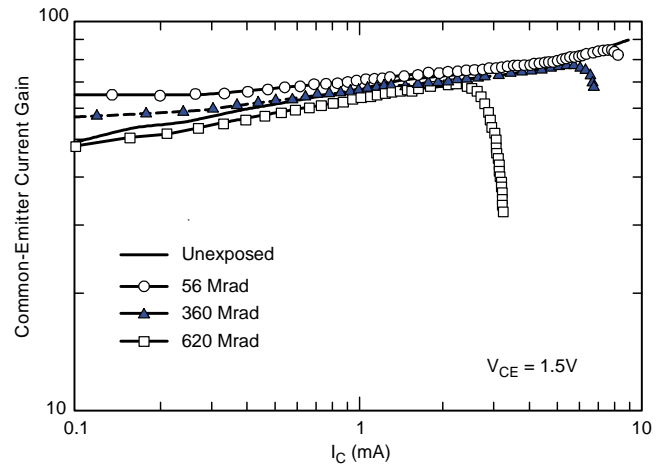

Figure 8. Total dose degradation of an InP/InGAAs heterojunction bipolar transistor.

B. Displacement Damage

Heterostructure-Based Transistors and MESFETs. Displacement damage is more critical for compound semiconductors than ionization damage. However, different mechanisms may be involved compared to displacement damage in silicon devices. Most compound semiconductors are only slightly affected by minority carrier lifetime damage either because they are majority carrier devices, or they are minority carrier devices with extremely narrow carrier transport dimensions (such as transistor base width). However, at high fluences carrier removal will alter the effective doping concentration. Typical carrier removal rates for high-energy protons are on the order of 40 cm^{-1}; this means that a 4% change in carrier concentration will occur for material doped to 10^{15} at a proton fluence of 10^{12} p/cm^2. Most high-frequency

compound semiconductor devices have doping concentration above 10^{16} cm^{-3}, and consequently they do not exhibit significant damage until they are exposed to radiation levels above 10^{13} p/cm^2.

Silicon-germanium bipolar transistors are beginning to dominant applications at very high frequencies. Figure 9 shows proton radiation test results for silicon-germanium heterojunction bipolar transistors that are intended for RF applications [34]. There is significant degradation at low currents, although it should be emphasized that the figure shows results at a relatively high proton fluence. However, typical RF applications use the device at high current densities where the degradation is extremely small (note the callout in the figure regarding normal biasing for RF applications). Thus, this device is useable at fluences above 10^{14} p/cm^2, far higher than the radiation levels encountered by most space systems.
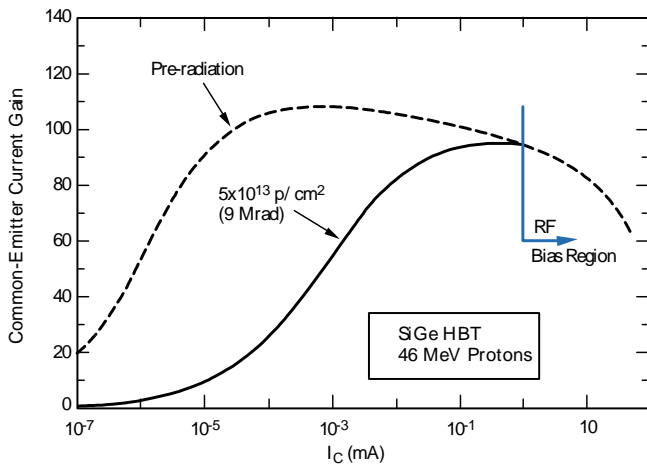
Figure 9. Proton degradation of a silicon-germanium heterojunction bipolar transistor.

Optoelectronics

Displacement damage is a much more severe issue for optoelectronic devices. There is a tremendous range in sensitivities due to differences in fabrication techniques and principles of operation.

LED Displacement Damage. Light emitting diodes can be fabricated in many different ways. One older method, still widely used, relies on *amphoteric* doping. This process uses a single type of dopant (silicon) in GaAs, which is n-type when grown at high temperatures, but is p-type when it is grown at low temperatures [35]. The junction is formed by gradually changing the temperature during the growth process. This process produces LEDs with very high efficiency because the material is closely compensated, reducing free carrier absorption; and the

energy of the emitted radiation is below the bandgap energy (due to the compensated doping), eliminating band-to-band absorption. These LEDs have graded junctions that extend over relatively long distances. Consequently, they require very long minority carrier lifetime in order to operate efficiently.

Modern LEDs are usually made with shallow, double heterojunctions that do not require long lifetime. These types of LEDs have much shorter turn-on times, but are less efficient. Consequently there are still many applications of the older amphoterically doped LEDs. Figure 10 shows how proton damage affects various types of LEDs [36]. Note that there is a difference of about two orders of magnitude in damage sensitivities. Amphoterically doped LEDs are so sensitive to proton damage that the proton fluence from a single solar flare can significantly degrade the LED.
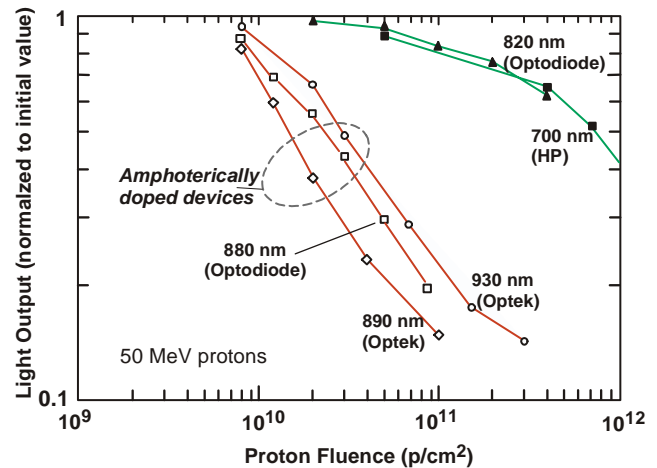
Figure 10. Proton degradation of various types of LEDs. Note the extreme sensitivity of amphoterically doped devices.

One important application of LEDs is in optocouplers. However, the type of LED within an optocoupler usually is not specified, only the overall electrical performance. Amphoterically doped LEDs are frequently used in optocouplers, resulting in extremely poor radiation performance [37]. Unless the manufacturer explicitly controls the type of LED, this can cause extreme variability in the radiation hardness of the optocoupler.

Laser Displacement Damage. Semiconductor lasers are far less affected by proton displacement damage than light-emitting diodes. The reason is that they use heterojunctions with thin layers and high carrier densities, and do not require long lifetimes for efficient operation. Displacement damage increases internal (non-radiative) losses, increasing the threshold

current as well as the slope efficiency [38,39]. However, the internal optical power level of a semiconductor laser is quite high, much higher than that of LEDs. Thus, there is less margin for change in operating characteristics. Figure 11 shows an example of the effect of proton damage on the output power characteristics of a semiconductor laser. Although the change in threshold current is relatively small, the laser diode must be driven at much higher internal power levels after irradiation in order to maintain light output, which will reduce reliability. Most space applications require that laser diodes operate well below maximum ratings to maintain reliable operation.
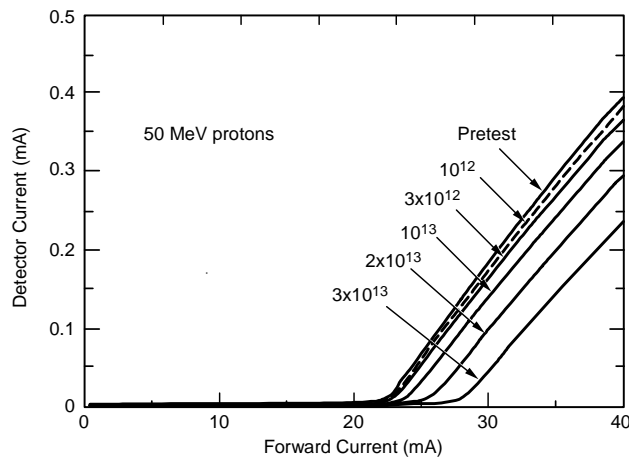

Figure 11. Degradation of the output power characteristics of a semiconductor laser after irradiation with high-energy protons.

In addition to degradation of the laser, most laser diodes include an internal monitor diode that is used to measure the light output. The output of the monitor diode is typically used in a control circuit that establishes a fixed light output condition from the laser. However, the monitor diode may also degrade from radiation, which can cause the laser to be driven into an operational region that is beyond the normal range, affecting reliability. In some cases the monitor diodes degrade more rapidly than the lasers [39]. Controlling operating temperature and maintaining light output over a restricted range are essential in order to use laser diodes in space.

C. Single-Particle Effects

Because of their fast response time, logic circuits made with compound semiconductors are highly sensitive to upset from cosmic rays and protons. Fabrication details play a large role. (The upset is caused by the generation of a short-duration charge when the cosmic ray or proton interacts with the device). The most sensitive devices are those made on a semi-insulating (SI) substrate. Excess carriers generated within the SI substrate can be collected by a MESFET or HFET structure, allowing the device to be upset with a particle that has lower specific charge generation (linear energy transfer) compared to a structure where charge collection is limited to the active region.

Another important factor is the parasitic bipolar transistor that is present in MESFET and HFET structures. Figure 12, after Hughlock, et al. [40], compares the single-event upset threshold LET and cross section for three different types of devices, all manufactured with 1-µm feature size. The reason for the high sensitivity of the GaAs MESFET is the high parasitic bipolar gain. The other two technologies have lower gain, which reduces single-event sensitivity. Hughlock, et al. observed the same response in special GaAs MESFETs that were fabricated without the gate region, demonstrating that the bipolar effect was the underlying mechanism for the high sensitivity of those devices.
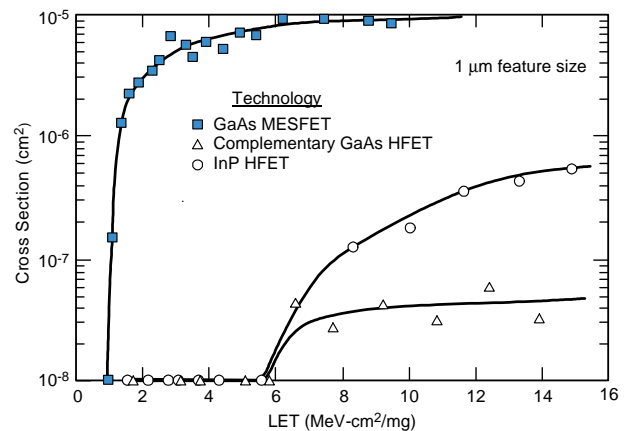

Figure 12. Single-event upset sensitivity of GaAs MESFETs (on a semi-insulating substrate) compared with other compound semiconductor logic devices.

More recent work by McMorrow, et al. showed that the same excess charge collection process observed for GaAs MESFETs is also present in high-electron mobility transistors fabricated with AlSb/InAs [41]. They performed charge-collection experiments on state-of-the-art devices with gate lengths of only 0.1 µm.

These results suggest that single-event upset sensitivity of advanced compound semiconductor devices may still be a problem for space use. The threshold LET is typically about 1 MeV-cm^2/mg, about a factor of three lower than the threshold LET of advanced silicon devices (such as memories and microprocessors), and so low that even alpha particles from packaging can cause upsets. The cross section of

compound semiconductors has typically been about two orders of magnitude higher than that of silicon devices with equivalent feature size because of the excess charge from parasitic bipolar devices.

Although most small-area compound semiconductor devices are extremely sensitive to single-event upset, they are usually not incorporated into high-density circuits (memories and processors, which are dominated by CMOS technology). Thus, the practical effect of the extreme sensitivity to transient pulses and logic errors is usually slight compared to CMOS technology in most system applications simply because there are relatively small numbers of flip-flops or other storage devices within the types of circuits that are designed with compound semiconductors.

However, there are cases where upset effects can be an issue, including high-speed fiber-optic data buses. The effect of the upsets is to increase the bit-error rate in space compared to terrestrial applications [42]. This can be overcome by increasing optical power, making the subsystem less sensitive to the short-duration "noise" pulses that are produced by ions in space.

VI. CONCLUSIONS AND FUTURE PREDICTIONS

This paper has discussed reliability and radiation hardness of compound semiconductors, pointing out how differences in material technology and properties as well as fabrication technology affect the overall reliability of these devices. It is important to understand that one cannot simply extend the knowledge of silicon technology to compound semiconductors.

The key issues for reliability stem from differences in fabrication, along with the requirement that some types of compound semiconductors have to operate at very high power densities in order to achieve maximum benefit. This, along with the lower thermal conductivity of GaAs (and some other compound semiconductor materials) increases the importance of packaging technology and thermal management to overall device reliability.

Another important issue is the design of transistors with extremely small dimensions. This places more demands on contacts and metallization, which can potentially affect reliability. Some advanced compound semiconductor devices use physical dimensions of 0.1 µm or less, and fabrication methods are still evolving for reliable manufacture of devices with such small dimensions.

From the standpoint of radiation hardness, most compound semiconductors are much less affected by ionization or proton displacement damage than silicon-based technologies. However, light-emitting diodes are an important exception. Older, highly efficient LEDs are among the most sensitive components to radiation damage from protons. This not only affects LED response, but also causes certain types of optocouplers to be highly sensitive to radiation damage in space applications.

Logic devices fabricated with compound semiconductors are highly sensitive to upset effects from cosmic rays and protons, and this can be an important effect for some applications. However, this limitation is relatively unimportant unless compound semiconductor circuits are being used with large numbers of storage elements, which is usually not the case. Thus, most compound semiconductor devices are excellent choices for space applications because of high radiation damage tolerance.

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